MECHANICAL PROPERTIES OF SEVERAL HONEYCOMB CORES

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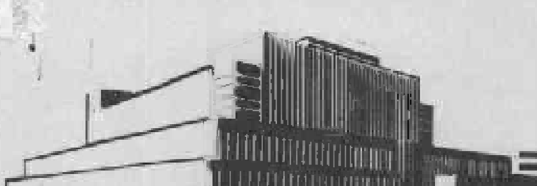

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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
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MECHANICAL PROPERTIES OF SEVERAL HONEYCOMB CORES[1]

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Summary

Mechanical properties of several aluminum and reinforced plastic honeycomb cores are presented along with details of the methods used to determine them. Properties that were evaluated included density, foil thickness, flatwise compressive strength, compressive modulus of elasticity, shear strength, and shear modulus. Analysis of experimental data includes relationships between compressive strength and density, between compressive and shear strength, and between shear properties in two principal directions.

Introduction

Lightweight structural panels suitable for use in modern flight vehicles can be produced by bonding facings of a thin strong material to a core of thick, low-density material. The need for suitable core material has resulted in production of honeycomb-like cores formed of thin sheet material. Composite constructions made with cores of this type and the successful application of this construction in structures requiring high strength-to-weight ratio have demonstrated its practicability.

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[2]Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

Previous evaluations of the properties of honeycomb cores have been reported in Forest Products Laboratory Reports Nos. 1849,[3] 1855,[4] and 1861.[5] Since these reports were prepared, more cores have become available and improvements in the fabrication of cores have been made. This study was undertaken to evaluate honeycomb cores of aluminum alloy 5052H39 that were commercially available. Some exploratory work was also done on core materials that were either in limited production or experimental in design, samples of which included: (1) other 5052H39 cores; (2) 2024T4 aluminum alloy cores; (3) an aluminum core with staggered cells; and (4) cores made of heat-resistant reinforced plastic. Because the successful design of composite constructions does not depend on core properties as much as it does on facing properties, no attempt was made to obtain enough samples to arrive at guaranteed minimum values, as would be done for many structural materials.

Description of Cores

Commercial Aluminum Cores

Four commercial aluminum honeycomb cores were obtained. These cores were of 5052H39 aluminum alloy foils with nominal thicknesses of 0.0007, 0.002, 0.003, and 0.004 inch expanded to nominal 1/4-inch hexagonal cells. The foils were pierced with fine holes to allow solvents to escape during bonding of a composite panel, and the core was designated as permeable by the manufacturer. Twelve 1/2-inch-thick slices were obtained of each of the cores.

Experimental Aluminum Cores

For exploratory evaluation, several experimental cores of aluminum honeycomb were obtained in thicknesses of either 5/8 or 1/2 inch. The 5/8-inch-thick slices included 0.0007-inch 5052H39 foil expanded to 1/4-inch cells, 0.001-inch 5052H39 foil expanded to 1/8-inch cells, and 0.004-inch 5052H39 foil expanded to 1/4-inch cells. The 1/2-inch-thick slices were of 0.002-inch 5052H39 foil corrugated to 1/4-inch cells, 0.003-inch 2024T4 foil corrugated to 1/4-inch cells, or 0.003-inch 2024T4 foil corrugated to 3/8-inch staggered cells.

Cores of 0.001- and 0.004-inch 5052H39 aluminum foil that were received in 5/8-inch thicknesses were cut to 1/2-inch thickness.

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[3] Kuenzi, Edward W. Mechanical Properties of Aluminum Honeycomb Cores, Forest Products Laboratory Report No. 1849, 1955.

[4] Kuenzi, Edward W., and Setterholm, V. C. Mechanical Properties of Aluminum Multiwave Cores, Forest Products Laboratory Report No. 1855, 1956.

[5] Kuenzi, Edward W. Mechanical Properties of Glass-Fabric Honeycomb Cores, Forest Products Laboratory Report No. 1861, 1957.

The foil of the cores with corrugated 1/4-inch cells was perforated with 1/32-inch holes for solvent ventilation.

The foil with modified 3/8-inch hexagon cells, in which adjacent ribbons were staggered or offset one-half their cell dimension in the ribbon direction, was unperforated. This cell configuration, shown in figure 1, allows easy bending of the core without severe anticlastic curvature.

Plastic Cores

Experimental cores of heat-resistant reinforced plastic were 1/2 inch thick and had 3/16-inch hexagon cells. They had a density of 9 pounds per cubic foot and were made of phenolic and silicone resins reinforced with glass fabric and asbestos mat.

Weights and Measurements

Pieces of core in the thicknesses received were trimmed square and weighed; where a large piece was received, a 2- by 2-foot square was cut from the piece, then the square weighed and measured to obtain the density in pounds per cubic foot (tables 1 through 4). Core thickness was measured to the nearest 0.001 inch and the other dimensions to 0.01 inch. Cores were weighed to the nearest gram on a laboratory balance.

Foil thicknesses from each sample of aluminum core were measured on a strip that was one cell in width cut perpendicular to the ribbon direction. A dial gage micrometer reading to 0.0001 inch and mounted in a rigid stand was used to measure the foil thickness. Measurements were estimated to one-tenth of a dial division, or 0.00001 inch. A 1/32-inch radius point was attached to the dial stem. The anvil was a steel ball of 1/16-inch diameter, which was mounted at the apex of a metal cone attached to the base of the dial-supporting stand. The anvil and dial stem were electrically connected in series with a bulb and battery, so that contact between them or through the core foil closed the circuit and lighted the bulb. Bonded-core foils were measured in areas clear of adhesive, which were found by moving the foil between the dial point and anvil until the bulb would light. No attempt was made to scrape adhesive from the foil, because scraping could also remove some aluminum and thus give incorrect thickness values.

Preparation of Specimens and Test Methods

Flatwise Compression

Flatwise compression specimens 2 by 2 inches square and with a nominal thickness of one-half inch were cut on a bandsaw. The foil ends of the flatwise compression specimens were reinforced to prevent their rolling and buckling when loaded. The top and bottom of the specimens were dipped in a refractory heat-resistant cement, which formed a 1/16-inch fillet on the foil edges when hardened. The reinforced plastic cores, as well as the aluminum cores, were end dipped before being loaded in flatwise compression.

Specimens that were cut from the reinforced plastic cores were divided into two groups. Specimens to be evaluated at room temperature, 250°, and 350° F. were conditioned at 75° F. and 50 percent relative humidity for at least 1 month. Specimens that were to be evaluated at 250° and 350° F. were then conditioned in an electric oven for 1/2 hour before load was applied. The remaining specimens were placed over water in a closed container for a minimum of 60 days where the temperature was maintained at 100° F. so that the relative humidity was essentially 100 percent before being evaluated. The specimens were removed from their storage conditions one at a time immediately before testing. The work was completed within 100 days from the start of the conditioning period.

Flatwise compression specimens were evaluated in a hydraulic testing machine. The rate of motion of the movable head was controlled between 0.0015 and 0.003 inch per minute, depending on the strength and stiffness of the specimen, so that the maximum load occurred in 3 to 6 minutes. Deformations were measured for some constructions, and the modulus of elasticity of the core is given in table 1. A deformation gage with a gage length of one-fourth inch was developed that was similar in mechanical arrangement to a Lamb's roller compressometer. Deformations were read in the same manner as with a Marten's mirror compressometer, the image of a crosshair projected on the movable mirror attached to one steel roller being reflected back to a graduated scale. The gage was made of stainless steel and was calibrated with a modified Zeiss optimeter. Figure 2 shows a specimen with the gage in place.

Shear

Core shear specimens 2 by 6 inches and of nominal 1/2-inch thickness were cut from core samples with a bandsaw. Core specimens were cut with the core ribbons oriented parallel and also perpendicular to the 6-inch length. Shear properties in two principal directions[6], parallel (TL) and perpendicular (TW) to the core ribbon, could be evaluated. Shear specimens that were cut from the reinforced plastic cores were then divided into two groups, and each group was conditioned in the same way as their corresponding groups of flatwise compression specimens. Core shear specimens were evaluated by the two-plate shear technique. The core shear specimen, therefore, had to be bonded between two steel plates 1/2 inch thick, 2 inches wide, and 8-1/2 inches long. The steel plates were first cleaned with a power-operated steel brush to remove any adhesive remaining from previous use. They were then wiped clean

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[6] Department of Defense. Sandwich Constructions and Core Materials; General Test Methods. Military Standard 401A, June 1956.

with acetone and etched in a solution of 10 parts concentrated sulfuric acid, 1 part sodium dichromate, and 30 parts distilled water for 10 minutes at 150° F.

After the etch bath, the plates were rinsed in steam and water, and wiped with a wet cloth. They were then wiped with a dry clean cloth and air dried for 30 minutes at 110° F. in a box equipped with a recirculating fan. Core specimens were brushed to remove loose material before they were bonded to the loading plates.

A uniform adhesive coating of from 6 to 22 grams, the weight being constant within each group of specimens, was applied to each of the clean, dry steel plates. The plates and core were assembled in a metal jig that alined the core with the plates, and the entire assembly was placed in a hydraulic press with electrically heated platens.

Aluminum core specimens were bonded with an epoxy-resin adhesive with 8 percent catalyst and were cured under a pressure of 15 pounds per square inch at 200° F. for 2 hours.

Reinforced plastic cores to be studied at 250° and 350° F. were bonded with the same adhesive system as the aluminum cores.

Cores of reinforced plastic that were to be studied after conditioning at 75° F. and 50 percent relative humidity were bonded with another epoxy-resin adhesive, which had 30 percent by weight of chopped glass fibers added to stiffen the adhesive. This adhesive was applied to loading plates previously coated with a cured vinyl phenolic liquid adhesive primer. The adhesive was finally cured for 2 hours at 10 pounds per square inch at 160° F., the bonding being done in the same room where the core was conditioned. The bonded specimens were stored in the conditioning room to allow them to return to equilibrium conditions before they were tested.

Reinforced plastic cores that were conditioned at 100° F. and 100 percent relative humidity were bonded with epoxy-resin adhesive, with 8 percent catalyst and 10 percent glass fibers by weight. The assembled specimens were enclosed in a plastic bag and placed under a pressure of 15 pounds per square inch in a cold press overnight. They were then placed in a humidity box at 150° F., with a wet-bulb reading of 135° F., for one more day to cure the adhesive further and to prevent the core from losing moisture. The bonded specimens were placed back in their storage trays at the original condition until they were tested.

In order to conduct the shear tests, opposite ends of the steel plates were fastened to links and hung in the testing machine as shown in figure 3. A tension load was applied to place a shear load on the core in the 6-inch direction. The movable head of the testing machine was controlled so it would travel between 0.01 and 0.03 inch per minute, depending upon the particular core construction; the speed was selected so that it would place a maximum shear load on the specimen in 3 to 6 minutes. Shear deformations were determined by measuring the displacement of the two loading plates with respect to each other. The first tests to measure the displacement were made with a Marten's mirror apparatus (fig. 4). Cores of 5052H39 aluminum, with 1/4-inch cells expanded from foils in thicknesses of 0.001, 0.002, 0.003, and 0.004 inch, were evaluated using the Marten's mirrors. Some additional specimens in foil thicknesses of 0.003 and 0.004 inch then were prepared and the shear tests repeated, using a dial gage reading to 0.0001 inch to measure shear displacement (fig. 3). Some tests at elevated temperatures with the reinforced plastic cores were made using the dial gage to measure displacements. Shear strain in the core was determined by dividing the measured displacement by the core thickness. Thus, the shear strain may be in error, as the measured displacement will include slip in the adhesive bond between the core and loading plates if it occurred. The slip was believed to be small where only a thin spread of adhesive was used, however, because the core could be pressed through the adhesive until it contacted the steel plates.

Presentation and Discussion of Results

Commercial Cores

Data for the commercially produced honeycomb cores of 5052H39 aluminum are given in table 1.

Measured foil thicknesses of these cores were within 10 percent of nominal values except with the foil of nominal 0.0007-inch thickness on which actual thicknesses of 0.00099 inch were measured. Computations of core density based on measured foil thicknesses were made using the formula,[3] $W = 450t/s$, in which W is core density in pounds per cubic foot, t is foil thickness, and s is cell size. The results were within 10 percent of actual core density.

Compressive moduli of elasticity were computed from deformations measured on cores of 0.002-, 0.003-, and 0.004-inch foil. Foil of 0.0007-inch thickness was not stiff enough to support the deformation-measuring apparatus. Average values given in table 1 were about 15 percent higher than would be expected from the weight of the cores. The expected elastic modulus of a core of 5052H39 aluminum alloy can be obtained as $E_T = 10{,}200{,}000\ W/168$, where W is the core density and 168[7] is the weight in pounds per cubic foot and 10,200,000[7] the elastic modulus in pounds per square inch of the alloy.

Foil stresses that were computed from core compressive strength values by means of the formula $F_t = 168F_T/W$ were found to vary from 12,000 pounds per square inch for the core of nominal 0.0007-inch foil to 30,300 pounds per square inch for the core of nominal 0.004-inch foil. Previous work[3] had shown the foil stress to be nearly constant at core failure. Compressive strength values are plotted versus core density in figure 5. The relationship between strength and density is not linear but may be fairly well

[7] Department of Defense. Strength of Metal Aircraft Elements. Military Handbook No. 5, 1959.

represented by the formula

$$F_T = 45W^{5/3}$$

where $\underline{F_T}$ is core compressive strength in pounds per square inch and $\underline{W}$ is core density in pounds per cubic foot.

Shear properties in planes parallel (TL) and perpendicular (TW) to the core ribbon direction are presented in table 1 for samples of the commercial core. All the shear specimens failed in the core itself except those of the 0.004-inch foil, which failed either in the core or in the bond between the core and plates. The results for specimens that failed in the bond between the core and plates are included in table 1, as extensive cell buckling was visible in the core before failure.

Shear deformation values were obtained using both the Marten's mirrors and a dial gage, and are shown in table 1. The values for shear modulus determined from dial gage data were consistently higher than the corresponding values from the Marten's mirror data, the maximum difference being about 30 percent.

When shear modulus values were calculated, the actual core thickness was reduced 0.00039 inch for every gram of adhesive because of the heavy adhesive spread used to bond the specimens. Shear modulus values for the TL plane were calculated using the equation[3] G_{TL} = 5,160,000W/456 where $\underline{W}$ is the core density. This is based on a foil modulus of rigidity of 3,850,000 pounds per square inch. Computed moduli of rigidity averaged about 15 percent less than the measured values.

A comparison of the moduli of rigidity in both directions is shown in figure 6. The relationship between the values ($G_{TL} = 0.41\ G_{TW}$) agrees with that given in a previous report.[3]

Buckling criteria applied to the cell walls did not provide a basis for estimating shear stresses at proportional limit or shear strength in the TL direction. Figure 7 shows the average values of shear strength plotted against the core density. The equations $F_{TL} = 110W-80$ and $F_{TW} = 55W-40$ appear to fit the data and could be used to estimate the shear strength of similar core of the same alloy. It is also apparent from these formulas that $F_{TW} = 1/2F_{TL}$. The relationship presented in the previous report[3] was $F_{TW} = 0.54T_{TL} + 35$.

It is shown in figure 7 that the shear strength is related to density, and, therefore, that core compressive strength is related to density; in figure 8 the relationship between shear strength and compressive strength is shown. The equation $F_{TL} = 0.594F_T$ presented in a previous report[3] agrees with the present data.

Experimental Cores

Compression and shear values were obtained for three expanded cores of 5052H39 aluminum foil (table 2). These cores were received in 5/8-inch thickness and the two heavier cores were cut to a 1/2-inch thickness for evaluation.

The densities of these cores are different than the cores reported earlier in this report; however, the nominal foil thicknesses are the same. When the compressive strength of the cores was calculated using the relationship to density presented previously, the calculated compressive strength values were within 15 percent of the measured values. Similarly, shear strength in the planes evaluated were calculated using the relationship presented previously. The calculated values of shear strength in the TL plane were within 10 percent of the measured values and in the TW plane were within 20 percent of the measured values for the two lighter cores. It was not possible to correlate the shear strength of the heaviest core to density as these specimens failed in the bond between the core and loading plate.

Mechanical properties for the few experimental aluminum cores that were evaluated at elevated temperatures are presented in table 3. Limited data on the shear properties are presented because of difficulty in failing the specimens and the limited amount of material available. The strength-to-density ratio in both compression and shear for the corrugated cores is less than for the expanded cores. This is due to the larger amount of adhesive used in fabricating the corrugated cores, which increases their density. The reduction in compressive strength was from 3 to 40 percent at 250° F. and from 16 to 57 percent at 350° F. Core of 2024T4 aluminum had the least loss in strength and the staggered-cell core had the largest reduction in strength at 250° and 350° F. As shear strength was shown previously to be related to compressive strength, the reduction in strength at elevated temperatures would be expected to be of the same magnitude. The limited values that are presented appear to substantiate this theory.

For the four reinforced plastic cores tested in flatwise compression, the phenolic cores were found to have much greater strength than the silicone cores at every exposure condition (table 4 and fig. 9). Phenolic core with glass fabric was a bit stronger than phenolic core with asbestos mat, but silicone core with glass fabric was weaker than silicone core with asbestos mat. All the plastic cores lost some strength when exposed to high humidity or elevated temperatures. After wet conditioning, the compressive strength of the phenolic cores of glass fabric or asbestos mat was reduced by about 25 percent, while the strength of the silicone cores was reduced by about 15 percent. The compressive strength of phenolic cores tested at 250° F. was reduced by 10 percent or less of the room temperature values, while the reduction in strength was as much as 60 percent for the silicone cores. The strength values at 350° F. were less than those at 250° F., but the additional loss in strength was less than 10 percent.

A few shear tests of reinforced plastic cores were made at 250° and 350° F. but these specimens failed in the bond between the core and loading plates, and the magnitude of any trends was obscured.

The effect of exposure to a high relative humidity on the reinforced plastic cores was clouded by the difficulty in bonding these specimens. The strength appeared to improve in the TL plane for all the cores except the silicone asbestos and to be reduced in the TW plane for all the cores.

Design Values

Core properties are of secondary importance in the design of structural sandwich constructions, because the facings are the primary load-carrying portions of sandwich. Therefore, it was not considered necessary to obtain "guaranteed minimum" values for cores as are usually obtained for the facing materials. By using the minimum value of 12 determinations of a property as a design value, the statement can be made that 78 percent of the population will exceed this minimum value 95 percent of the time.[8]

Of secondary importance to designers are the elastic properties of the cores; that is, compressive modulus of elasticity and shear modulus. The modulus of elasticity, E_T, and the shear modulus, G_{TL} or G_{TW}, are contained in parameters for determining the wrinkling of sandwich facings under edge load. The shear moduli, G_{TL} or G_{TW}, are also involved in parameters for describing the buckling of sandwich under edge load and for determining the deflection of sandwich under transverse load. Since the values of these elastic properties are of secondary importance in design, the values chosen are near the average for the particular core rather than minimum values. Entire stress-strain curves for use in design are presented in figures 10 to 16. The curves were drawn by first plotting the stress-strain data for the specimen having the least strength, thus defining the general shape of the curve and locating the maximum stress point with its associated strain. Then the minimum proportional limit stress level (not necessarily the proportional limit stress for the same specimen that had least strength) was located on the curve sheet as a horizontal line. The initial part of the stress-strain curve was then located with a slope near to the average modulus and so that the curve could be faired in to fit the portion beyond proportional limit.

Conclusions

An analysis of the properties of cores in this report by means of previous empirical formulas shows that the mechanical properties of aluminum honeycomb core can be predicted approximately if core density is known.

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[8]Wilks, S. S. Sampling and Its Uncertainties. American Society for Testing Materials Proceedings, Vol. 48, 1955.

Table 1.--Mechanical properties at room temperature of honeycomb core of commercially produced permeable 5052H39 aluminum foil of four thicknesses expanded to 1/4-inch cells

	Average core density	Average foil thickness	Flatwise compression: Proportional limit stress	Flatwise compression: Maximum stress	Flatwise compression: Modulus of elasticity	Shear parallel to core ribbon (TL)[1]: Proportional limit stress	Shear parallel to core ribbon (TL)[1]: Maximum stress	Shear parallel to core ribbon (TL)[1]: Shear modulus G_{TL}	Shear perpendicular to core ribbon (TW)[1]: Proportional limit stress	Shear perpendicular to core ribbon (TW)[1]: Maximum stress	Shear perpendicular to core ribbon (TW)[1]: Shear modulus G_{TW}
	Lb. per cu. ft.	In.	P.s.i.	P.s.i.	1,000 p.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.
					CORE OF NOMINAL 0.0007-INCH FOIL						
	2.01	0.00099	...	132	...	90	138	24,200	38	89	11,500
	1.98	.00099	...	135	...	80	138	19,200	36	80	9,900
	2.01	.00100	...	144	...	92	140	21,900	35	81	10,300
	1.99	.00099	...	148	...	77	135	21,400	37	80	10,200
	1.97	.00099	...	131	...	93	143	22,300	39	81	10,600
	2.00	.00100	...	151	...	85	145	16,400	40	78	10,500
	2.02	.00099	...	161	...	87	135	19,600	27	72	9,000
	2.02	.00099	...	143	...	80	134	23,500	27	66	8,400
	2.01	.00100	...	163	...	87	134	19,100	36	77	10,200
	1.99	.00099	...	134	...	92	132	19,400	36	82	11,700
	1.97	.00099	...	154	...	102	139	19,800	36	78	11,100
	1.96	.00099	...	142	...	83	125	18,300	36	79	9,300
Av.	1.99	.00099	...	145	...	87	136	20,400	35	79	10,200
Min.	1.96	.00099	...	131	...	77	125	16,400	27	66	8,400
Max.	2.02	.00100	...	163	...	102	145	24,200	40	89	11,700
					CORE OF NOMINAL 0.002-INCH FOIL						
	3.88	.00200	332	451	236	186	327	48,900	117	163	16,600
	3.93	.00200	357	487	350	187	356	50,300	119	175	19,400
	3.97	.00201	322	444	248	183	364	52,000	118	165	18,200
	3.94	.00200	325	415	252	185	325	47,000	115	168	18,700
	3.87	.00200	455	515	236	203	350	50,500	119	167	17,200
	3.94	.00200	275	488	256	214	352	48,000	122	159	17,900
	3.99	.00204	298	515	169	183	371	50,800	109	170	19,400
	3.88	.00201	423	508	205	189	322	47,100	122	159	18,000
	3.89	.00201	372	493	264	188	337	46,800	117	169	20,800
	3.90	.00201	348	480	394	218	330	46,600	122	167	15,500
	3.96	.00204	325	513	224	202	354	47,900	127	161	17,800
	3.92	.00204	322	415	276	185	317	36,900	122	166	25,500
Av.	3.92	.00201	346	477	259	194	342	47,700	119	166	18,700
Min.	3.87	.00200	275	415	169	183	317	36,900	109	159	15,500
Max.	3.99	.00204	455	515	394	218	371	52,000	127	175	25,500
					CORE OF NOMINAL 0.003-INCH FOIL						
	6.14	.00350	704	841	600	294	538	82,800	182	297	30,700
	5.73 (5.73)	.00316	589	844	520	374 (330)	544 [2](517)	76,800 (65,300)	166 (206)	267 (308)	24,500 (38,900)
	5.52	.00300	619	842	423	329	485	62,000	159	256	24,300
	5.44	.00301	650	875	360	310	502	76,000	159	261	25,400
	5.90 (5.90)	.00307	785	931	410	340 (311)	591	73,500 (79,000)	151 (197)	290 (299)	27,000 (31,500)
	6.00	.00301	895	1,020	355	387	622	76,800	175	285	25,600
	5.80 (5.80)	.00301	670	867	352	297 (343)	573 [2](577)	64,300 (87,400)	183 (205)	283 (294)	25,100 (32,100)
	5.92 (5.92)	.00301	...	915	...	366 (358)	581 [2](560)	76,800 (89,800)	158 (157)	272 (288)	25,400 (32,500)
	6.04	.00301	...	952	...	347	588	77,500	179 (173)	287	25,700
	5.96 (5.96)	.00301	...	905	...	383 (344)	576 [2](535)	82,800 (81,400)	183	289 (306)	26,800 (35,600)
	5.96 (5.96)	.00301	742	835	473	383 (310)	606 (555)	81,500 (71,400)	184 (189)	268 (294)	24,300 (33,300)
	6.12	.00315	...	960	...	372	575	74,100	170	262	23,400
Av.	5.88 (5.88)	.00308	707	899	437	349 (335)	565 [3](566)	75,500 (79,100)	171 (188)	276 (298)	25,700 (34,000)
Min.	5.44 (5.73)	.00300	589	835	352	294 (310)	485 (555)	62,000 (65,300)	151 (157)	256 (288)	23,400 (31,500)
Max.	6.14 (5.96)	.00350	895	1,020	600	387 (358)	622 (577)	82,800 (89,800)	184 (206)	297 (308)	30,700 (38,900)
					CORE OF NOMINAL 0.004-INCH FOIL						
	7.69	.00430	1,210	1,430	480	432	783	105,000	166	376	36,400
	7.90	.00430	970	1,370	519	498	755	116,000	215	396	37,100
	7.76 (7.76)	.00430	1,090	1,333	519	511 (390)	[2]640 [2](700)	109,000 (104,000)	233 (208)	379 (394)	30,900 (38,700)
	7.54	.00430	1,200	1,460	560	505	770	105,000	215	376	31,000
	7.65 (7.65)	.00430	...	1,410	...	484 (533)	[2]812 [2](770)	101,000 (118,000)	215 (233)	380 (404)	37,300 (42,200)
	7.77	.00430	...	1,540	...	517	[2]725	106,000	232	373	29,600
	7.85	.00430	1,187	1,473	541	460	[2]810	122,000	230	393	32,300
	7.64 (7.64)	.00430	1,030	1,380	689	501 (387)	[2]827 [2](672)	114,000 (123,000)	251 (200)	382 (371)	28,400 (37,400)
	7.72 (7.72)	.00430	748	1,340	428	465 (508)	[2]625 [2](672)	107,000 (128,000)	230 (217)	376 (410)	30,400 (46,900)
	7.69 (7.69)	.00430	837	1,290	527	428 (459)	[2]679 [2](680)	96,900 (126,000)	196 (242)	384 (410)	30,700 (46,700)
	7.72 (7.72)	.00430	1,175	1,350	504	429 (449)	776 [2](649)	110,000 (91,600)	197 (192)	403 (376)	34,200 (36,700)
	7.56	.00430	670	1,250	583	512	[2]764	112,000	217	381	28,700
Av.	7.70 (7.70)	.00430	1,012	1,386	535	479 (454)	[3]771 [2](690)	109,000 (115,000)	216 (215)	383 (394)	32,300 (41,400)
Min.	7.54 (7.64)	.00430	670	1,250	428	428 (387)	755 [2](649)	96,900 (91,600)	166 (192)	373 (371)	28,400 (36,700)
Max.	7.90 (7.76)	.00430	1,210	1,540	689	517 (533)	783 [2](770)	122,000 (128,000)	251 (242)	403 (410)	37,300 (46,900)

[1]Values shown were obtained with Marten's mirror apparatus. Values shown in parentheses were obtained with dial gage using matched specimens.

[2]Failure in bond between core and loading plates.

[3]Average of specimens that did not fail in bond between core and loading plates.

Table 2.--Mechanical properties at room temperature of honeycomb core of limited production of permeable 5052H39 aluminum in various foil thicknesses expanded to 1/4- or 1/8-inch cells[1]

	Core density[2]	Foil thickness[3]	Flatwise compression	Shear parallel to core ribbons (TL)			Shear perpendicular to core ribbons (TW)		
			Maximum stress	Proportional limit stress	Maximum stress	Shear modulus G_{TL}	Proportional limit stress	Maximum stress	Shear modulus G_{TW}
	Lb. per cu. ft.	In.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.
	0.0007-INCH FOIL EXPANDED TO 1/4-INCH CELLS								
	1.59	....	110	29	107	22,800	38	55	5,210
	1.55	....	120	38	101	19,500	17	53	7,720
	1.64	....	124	42	100	16,700	17	56	7,390
	.....	....	124	33	103	21,900	13	57	10,700
	.....	....	126	50	106	19,900	15	57	8,060
	.....	....	101	29	100	21,400	15	55	7,290
	.....	....	107	.....	.....	.....	.....	.....	.....
	.....	....	114	.....	.....	.....	.....	.....	.....
	.....	....	113	.....	.....	.....	.....	.....	.....
	.....	....	107	.....	.....	.....	.....	.....	.....
Av.	1.59	0.00089	115	37	103	20,400	19	55	8,060
Min.	1.55	.00085	101	29	100	16,700	13	53	5,210
Max.	1.64	.00095	126	50	107	22,800	38	57	10,700
	0.004-INCH FOIL EXPANDED TO 1/4-INCH CELLS								
	7.60	....	1,430	300	[4]525	105,500	267	385	38,100
	7.56	....	1,370	400	[4]610	104,000	250	365	41,700
	7.42	....	1,370	375	[4]570	93,800	267	[4]373	40,400
	.....	....	1,290	400	[4]500	99,000	250	[4]371	41,700
	.....	....	1,220	400	[4]540	104,000	267	406	43,000
	.....	....	1,220	350	[4]475	92,200	283	408	41,700
	.....	....	1,290	.....	.....	.....	.....	.....	.....
	.....	....	1,290	.....	.....	.....	.....	.....	.....
	.....	....	1,340	.....	.....	.....	.....	.....	.....
	.....	....	1,280	.....	.....	.....	.....	.....	.....
Av.	7.53	.0044	1,300	370	535	99,800	264	391	41,100
Min.	7.42	.0043	1,220	300	475	92,200	250	365	38,100
Max.	7.56	.0045	1,430	400	610	105,500	283	408	43,000
	0.001-INCH FOIL EXPANDED TO 1/8-INCH CELLS								
	4.51	....	562	233	395	50,800	175	226	27,800
	4.53	....	631	250	394	59,500	183	232	30,500
	4.50		616	300	402	58,800	192	229	30,200
	.....	....	490	300	407	61,200	183	228	30,400
	.....	....	628	233	373	60,700	183	226	28,300
	.....	....	530	283	384	55,300	183	227	29,500
	.....	....	570	.....	.....	.....	.....	.....	.....
	.....	....	577	.....	.....	.....	.....	.....	.....
	.....	....	631	.....	.....	.....	.....	.....	.....
	.....	....	540	.....	.....	.....	.....	.....	.....
Av.	4.51	.00136	578	266	392	57,700	183	228	29,400
Min.	4.50	.00130	490	233	373	55,300	175	226	27,800
Max.	4.53	.00140	631	300	407	61,200	192	232	31,400

[1]A single 5/8-inch-thick piece of each core was received; the two heavier cores were cut to a 1/2-inch thickness for testing.

[2]The sample of core was cut into three pieces and the density of each piece was calculated.

[3]Based upon 60 to 100 foil-thicknesses measurements.

[4]Specimen failed in bond between core and loading plates.

Table 3.--Properties[1] of four types of aluminum honeycomb cores that were in limited production or experimental in design

Properties at -	Core density	Foil thickness	Flatwise compression: Maximum stress	Shear parallel to core ribbons (TL): Proportional limit stress	Shear parallel to core ribbons (TL): Maximum stress	Shear parallel to core ribbons (TL): Shear modulus G_{TL}	Shear perpendicular to core ribbons (TW): Proportional limit stress	Shear perpendicular to core ribbons (TW): Maximum stress	Shear perpendicular to core ribbons (TW): Shear modulus G_{TW}
	Lb. per cu. ft.	In.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.
0.002-INCH 5052H39 PERFORATED FOIL CORRUGATED TO 1/4-INCH CELLS									
Room temperature	5.49		380	197	315	87,500	145	235	61,100
Do	5.54		400	195	319	64,700	125	186	35,800
Do			410	206	318	65,500	124	186	37,400
Do				167	323	[2]82,400	125	191	[2]38,600
Average	5.52	0.002	397	191	319	75,030	130	199	43,220
250° F.			280	115	[3]320	37,000	58	190	16,900
250° F.			290	132	258	[2]44,500			
250° F.			340	83	[3]248	[2]48,500			
Average			303	110	258	43,300	58	190	16,900
350° F.			244						
350° F.			255				36	84	[2]5,660
350° F.			215				32	71	[2]5,610
Average			238				34	78	5,640
Room temperature	4.54		475	248	373	77,200	155	216	38,100
Do	4.55		510	229	358	70,000			
Do	4.55			279	360	64,600			
Average	4.55	.002	492	252	364	70,600	155	216	38,100
250° F.			453	198	315	45,100	115	181	17,200
250° F.			482	188	299	45,300	124	187	17,600
250° F.			500	207	331	47,400	116	195	22,250
Average			478	197	315	45,900	118	188	19,000
350° F.			325	50	171	16,420	29	77	5,660
350° F.			346	67	193	18,750	29	78	5,560
350° F.			343	90	183	12,900	37	83	5,160
Average			338	69	182	16,020	32	79	5,460

(Sheet 1 of 2)

Table 3.--Properties[1] of four types of aluminum honeycomb cores that were in limited production or experimental in design (continued)

Properties at -	Core density	Foil thick-	Flatwise compression	Shear parallel to core ribbons (TL)			Shear perpendicular to core ribbons (TW)		
			Maximum stress	Propor-tional limit stress	Maximum stress	Shear modulus G_{TL}	Propor-tional limit stress	Maximum stress	Shear modulus G_{TW}
	Lb. per cu. ft.	In.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.
0.003-INCH 2024T4 PERFORATED ALUMINUM FOIL CORRUGATED TO 1/4-INCH CELLS									
Room temperature	6.03		657	250	494	78,400	149	258	43,200
Do	6.03		620	252	455	84,000	158	299	61,900
Do	6.05		725	234	450	76,800	149	294	49,800
Do	6.01		716						
Do	6.04		620						
Do			665						
Average	6.03	0.0025	670	245	466	79,800	152	284	51,600
250° F.			656				150	261	37,400
250° F.			596				141	275	37,200
250° F.			634						
250° F.			640						
250° F.			642						
250° F.			652						
Average			640				145	268	37,300
350° F.			490	75	138	14,350	41	148	14,670
350° F.			610	61	[3]97	12,760	54	137	12,650
350° F.			590	44	[3]166	20,900	45	165	13,250
Average			563	60	138	16,000	47	150	13,520
0.003-INCH FOIL CORRUGATED TO 3/8-INCH STAGGERED CELLS									
Room temperature	3.43		202	100	167	56,100	43	68	13,600
Do	3.41		240	116	174	57,250	42	65	12,950
Do	3.74		236	118	183	56,550	44	62	12,450
Do	3.61								
Average	3.55	.003	226	111	175	56,630	43	65	13,000
250° F.			157	46	100	23,390	25	45	4,920
250° F.			106	46	90	20,980	24	41	4,410
250° F.			145	29	107	29,780	31	50	5,900
Average			136	40	99	24,720	27	45	5,080
350° F.			115	17	48	8,540	7	29	2,740
350° F.			71	11	44	9,800	11	32	2,450
350° F.			105	14	46	8,640	11	27	1,780
Average			97	14	46	8,990	10	29	2,320

[1]Shear deformation measured with Marten's mirrors.

[2]Shear deformation measured with dial gages.

[3]Failure occurred in bond between specimen and loading plates.

(Sheet 2 of 2)

Table 4.--Properties[1] of reinforced plastic honeycomb cores with 3/16-inch hexagonal cells and densities of 9 pounds per cubic foot

Properties at -	Core density	Flatwise compression			Shear parallel to core ribbons (TL)			Shear perpendicular to core ribbons (TW)		
		Proportional limit stress	Maximum stress	Modulus	Proportional limit stress	Maximum stress	Shear modulus G_{TL}	Proportional limit stress	Maximum stress	Shear modulus G_{TW}
	Lb. per cu. ft.	P.s.i.	P.s.i.	1,000 p.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.
PHENOLIC-RESIN-IMPREGNATED GLASS FABRIC										
Room temperature	8.77	1,050	1,670	150	233	[2]682	71,500	158	463	23,200
Do	8.77	930	1,660	208	262	[2]508	60,100	144	457	53,800
Do			1,690		284	[2]634	58,600	177	472	24,300
Do					286	[2]650	64,000			
Average	8.77	990	1,670	179	266	618	63,600	160	464	33,800
100° F., 100 percent relative humidity		729	1,304	98	262	[2]552	75,800		351	
Do		864	1,250	91	227	[2]614	67,400		358	
Do			1,230		218	670	62,800	116	343	23,150
Do					230	646	40,600	132	344	21,020
Do								117	371	21,500
Do										
Average		796	1,261	94	234	[3]658	61,700	122	353	21,890
250° F.		990	1,730	134	32	[2]86	7,000	44	[2]95	7,060
250° F.		1,190	1,600	119	44	[2]79	7,380	44	[2]88	6,680
250° F.			1,600		36	[2]96	13,200	44	[2]103	7,000
Average		1,090	1,640	126	37	87	9,190	44	95	6,910
350° F.		1,350	1,610	108	105	[2]305	27,400	72	[2]230	11,600
350° F.		330	1,270	91	120	[2]376	26,700	64	[2]263	12,400
350° F.		840	1,620	143	96	[2]300	24,800	74	[2]209	12,500
Average		840	1,500	114	107	327	26,300	70	234	12,200
PHENOLIC-RESIN-IMPREGNATED ASBESTOS FIBERS										
Room temperature	9.29	953	1,580	153	304	[2]439	57,000	160	460	32,500
Do	9.30	990	1,856	244	225	[2]387	68,300	175	439	28,900
Do			1,250		406	[2]598	55,400	192	455	33,100
Do					402	[2]524	64,400			
Do					281	[2]520	63,200			
Do					282	562	63,200			
Average	9.30	971	1,562	198	316	[3]562	61,900	176	451	31,500
100° F., 100 percent relative humidity		906	1,288	168	245	[2]456	42,900	163	338	27,500
Do		524	932	97	277	[2]455	52,100	162	341	25,400
Do		976	1,297	137	244	556	53,600	164	475	40,300
Do					326	562	42,900	196	453	35,600
Do					281	602	42,300	245	434	32,800
Do					293	566	37,800			
Average		802	1,172	134	278	[3]572	45,300	186	408	32,300
250° F.		1,068	1,610	101	278	[2]562	47,600	32	[2]92	9,180
250° F.		495	1,327	107	161	[2]650	54,000	24	[2]67	10,270
250° F.		739	1,275	83				26	[2]62	9,640
Average		767	1,404	97	220	606	50,800	27	74	9,700
350° F.		690	1,288	81	18	[2]43	3,880	16	[2]48	4,680
350° F.		887	1,300	95	16	[2]43	3,770	22	[2]48	3,850
350° F.		857	1,357	72	18	[2]35	3,010	20	[2]41	3,420
Average		811	1,315	83	17	40	3,550	19	46	3,980

Table 4.--Properties[1] of reinforced plastic honeycomb cores with 3/16-inch hexagonal cells and densities of 9 pounds per cubic foot (continued)

Properties at -	Core density	Flatwise compression: Proportional limit stress	Flatwise compression: Maximum stress	Flatwise compression: Modulus	Shear parallel to core ribbons (TL): Proportional limit stress	Shear parallel to core ribbons (TL): Maximum stress	Shear parallel to core ribbons (TL): Shear modulus G_{TL}	Shear perpendicular to core ribbons (TW): Proportional limit stress	Shear perpendicular to core ribbons (TW): Maximum stress	Shear perpendicular to core ribbons (TW): Shear modulus G_{TW}
	Lb. per cu. ft.	P.s.i.	P.s.i.	1,000 p.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.
SILICONE-RESIN-IMPREGNATED ASBESTOS FIBERS										
Room temperature	8.74	234	598	119	232	[2]514	60,900	117	273	21,000
Do	8.68	189	758	186	116	[2]423	50,000	66	271	24,200
Do	8.65	375	756	132	151	436	64,000	116	252	18,000
Do	8.66				134	484	50,300			
Do	8.79				167	442	49,000			
Do					183	442	41,500			
Average	8.70	266	704	146	164	[3]451	52,600	100	265	21,100
100° F., 100 percent relative humidity		278	618	101	230	468	58,400	73	228	19,100
Do		236	614	76	178	416	53,600	97	219	17,300
Do		223	606	57	164	427	56,000	98	216	17,600
Average		246	613	78	191	437	56,000	89	221	18,000
250° F.		242	382	40	97	244	23,450	10	39	3,780
250° F.		293	456	59	41	[2]91	10,470	24	49	2,980
250° F.		207	499	65	49	[2]101	10,350	25	48	2,520
Average		247	446	55	62	[3]244	14,760	20	45	3,090
350° F.		172	424	55	14	[2]52	10,050	14	[2]51	3,060
350° F.		220	368	34	16	[2]52	8,960	10	[2]35	2,970
350° F.		172	408	39	16	[2]49	7,040	14	[2]49	3,690
Average		188	400	43	15	51	8,680	13	45	3,240
SILICONE-RESIN-IMPREGNATED GLASS FABRIC										
Room temperature		219	516	109	100	254	8,100	58	163	5,800
Do		124	532	241	100	254	9,000	59	138	4,100
Do		278	586	89				58	160	14,900
Average	[4]8.52	207	540	146	100	254	8,550	58	154	8,270
100° F., 100 percent relative humidity		240	394	99	37	270	21,400	38	138	6,680
Do		235	468	72	29	266	21,100	29	131	6,800
Do		303	513	56	74	257	12,700	29	117	5,070
Do					58	242	16,200	46	129	5,570
Do					83	269	43,100	45	128	5,170
Do					65	263	14,400	29	120	5,830
Average		259	458	76	59	261	21,500	36	127	5,850
250° F.		170	230	25	24	[2]86	1,950	20	68	1,390
250° F.			207		29	[2]87	2,130	25	67	1,090
250° F.		92	224	18	32	[2]85	2,260	22	65	960
Average		131	220	21	28	86	2,110	22	67	1,150
350° F.		136	206	42	31	82	2,110	11	36	590
350° F.		109	206	69	24	83	2,910	19	41	740
350° F.		80	156	29				20	51	1,420
Average		108	190	46	28	82	2,510	16	43	920

[1]Shear deformation measured with dial gage.

[2]Failure occurred in bond between core and loading plates.

[3]Average of specimens that failed in the core.

[4]Average of 10 values ranging from 7.80 to 8.91 pounds per cubic foot.

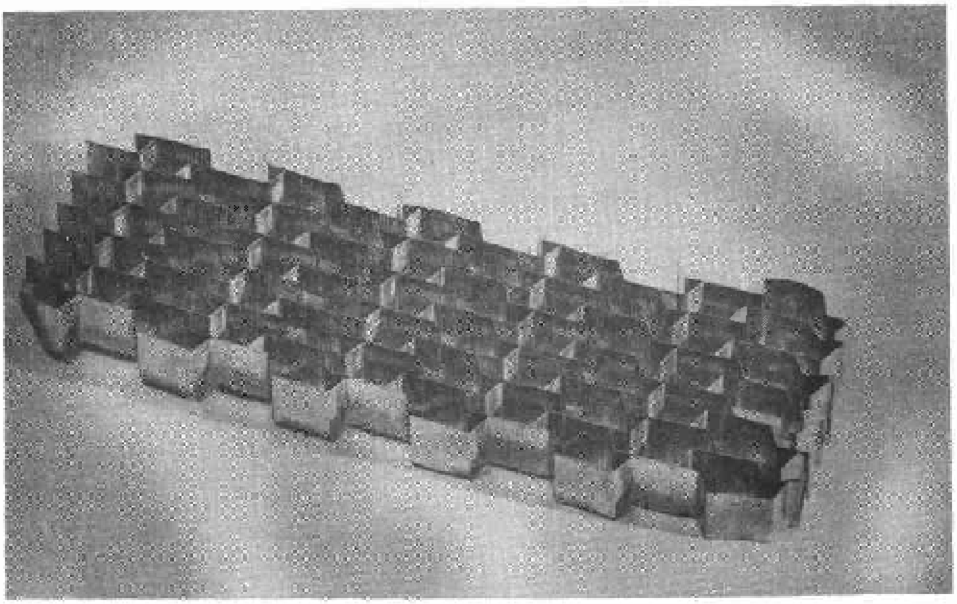

Figure 1.--Aluminum honeycomb core with staggered cells.

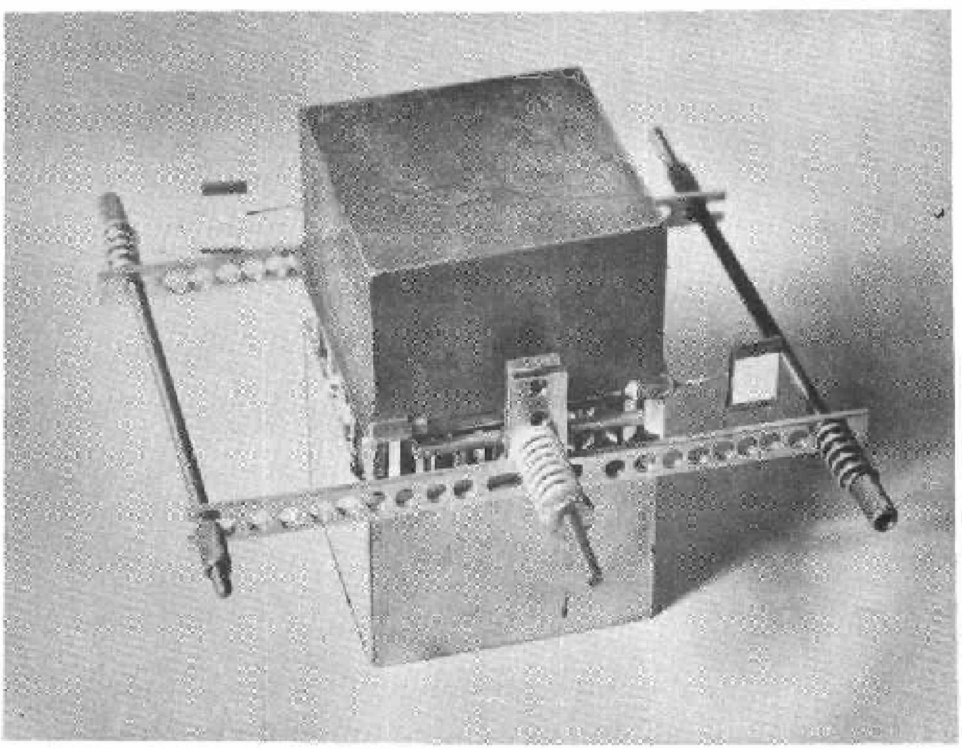

Figure 2.-- Flatwise compression specimen with steel loading blocks and deformation gage mounted in position.

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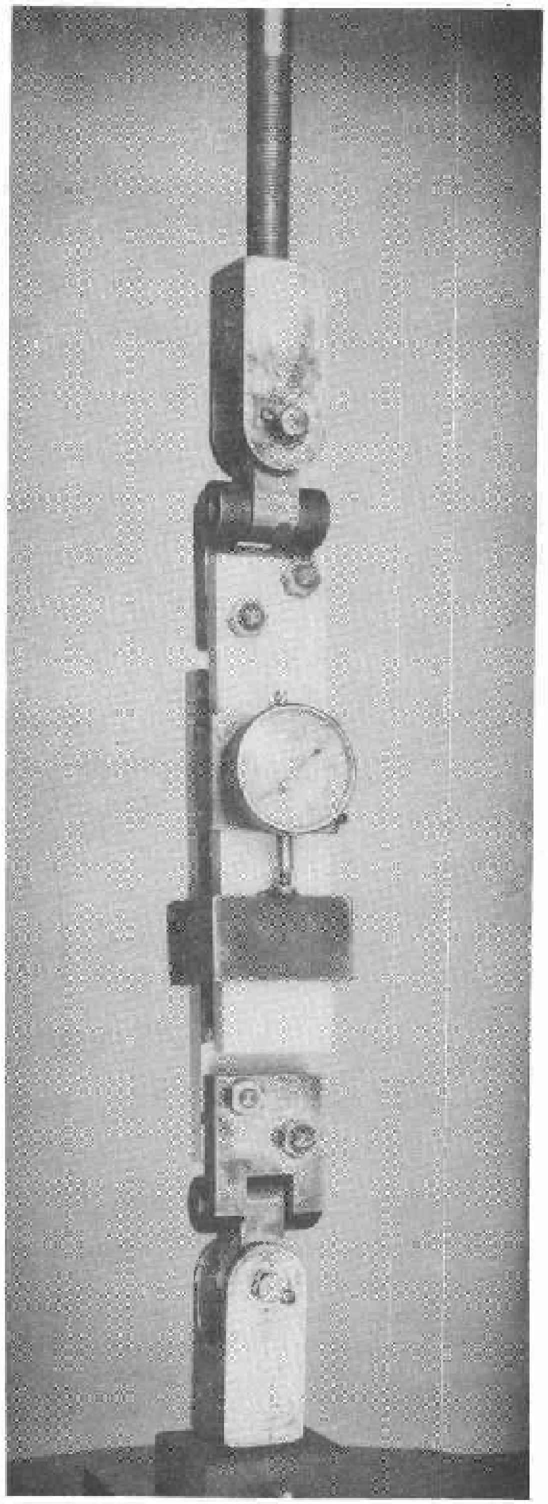

Figure 3.--Apparatus for shear test showing steel plates, specimen, and dial arrangement for measuring deformation between plates.

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Report No. 1887

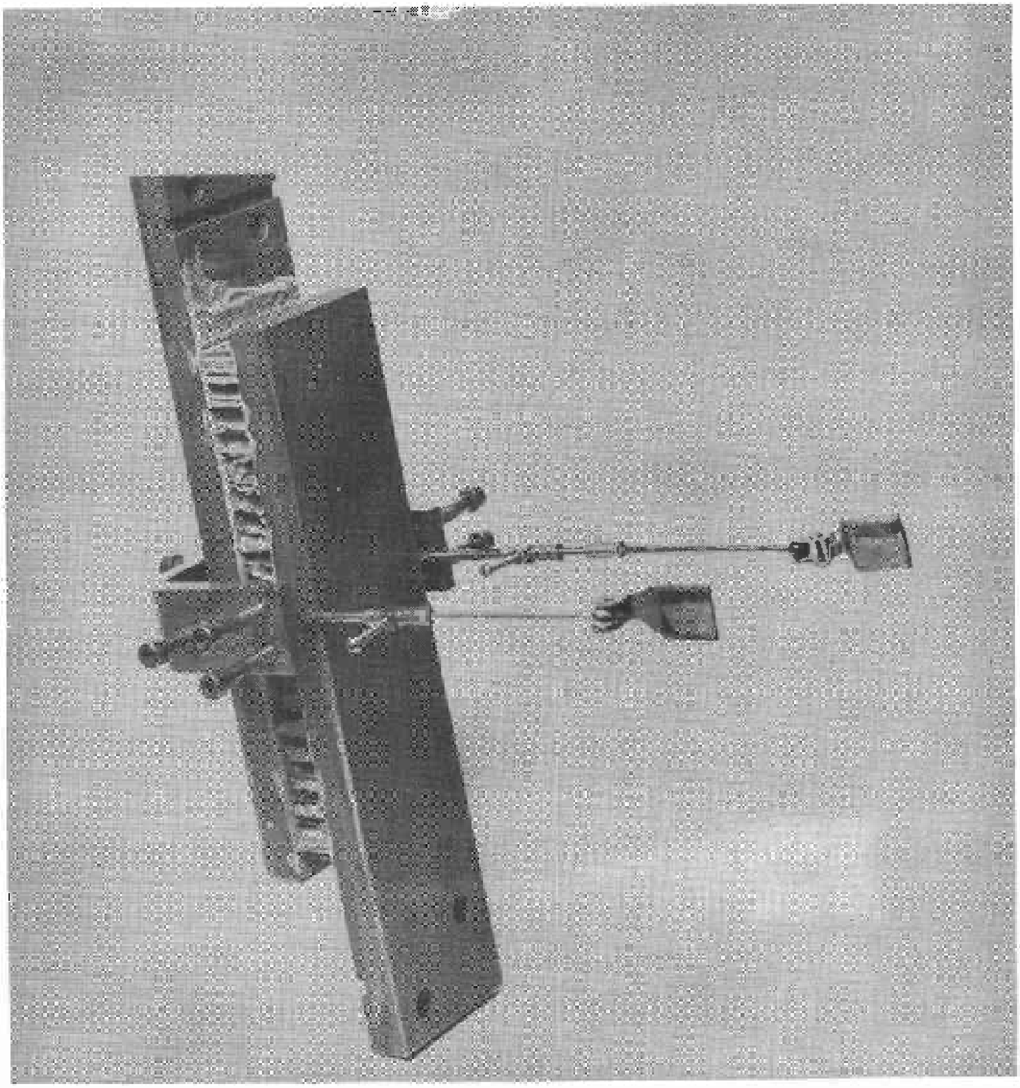

Figure 4. --Shear specimen bonded between steel plates showing the Marten's mirror apparatus for measuring displacement of steel loading plates.

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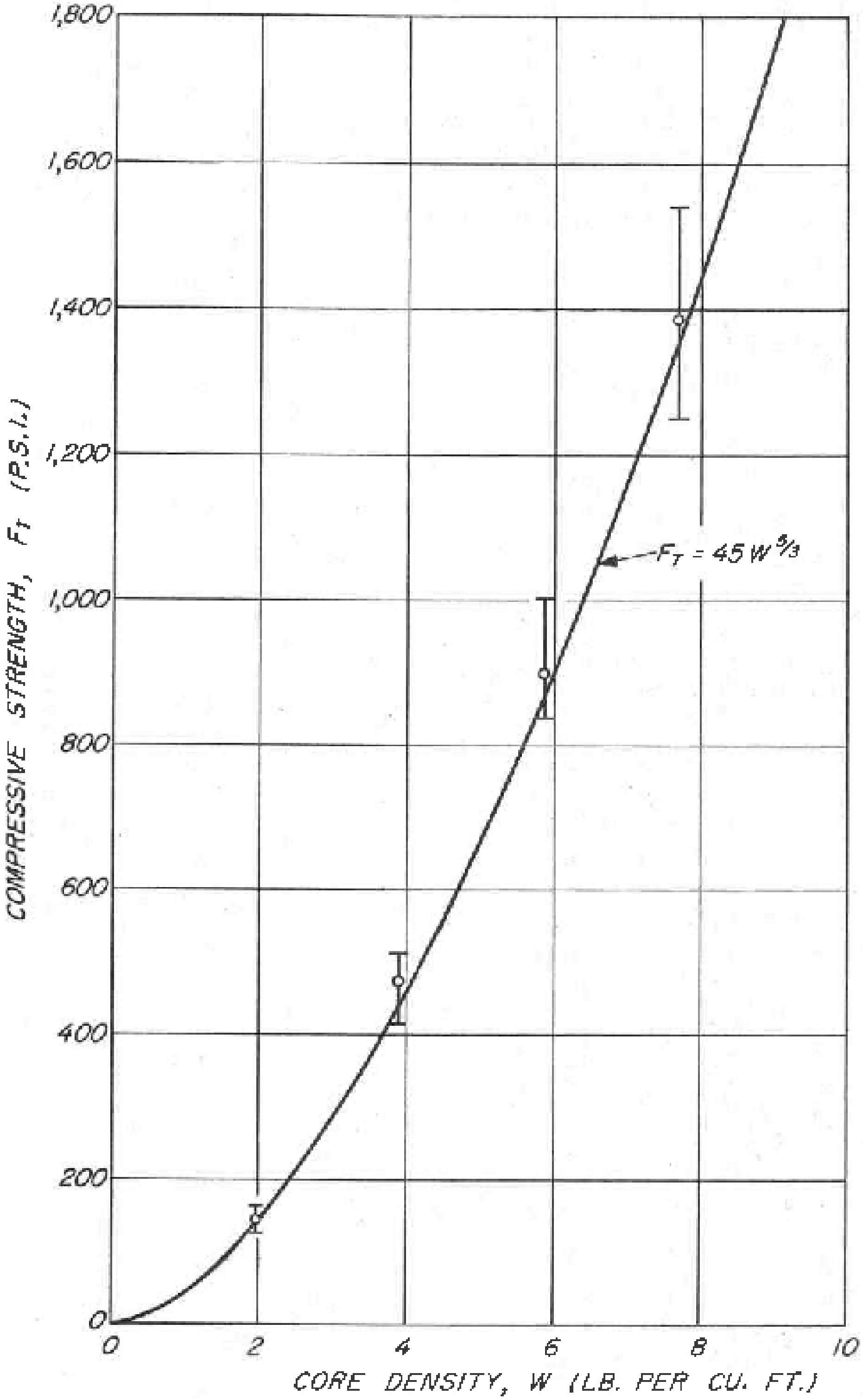

Figure 5. --Minimum, average, and maximum compressive strength values of honeycomb cores of 5052H39 aluminum.

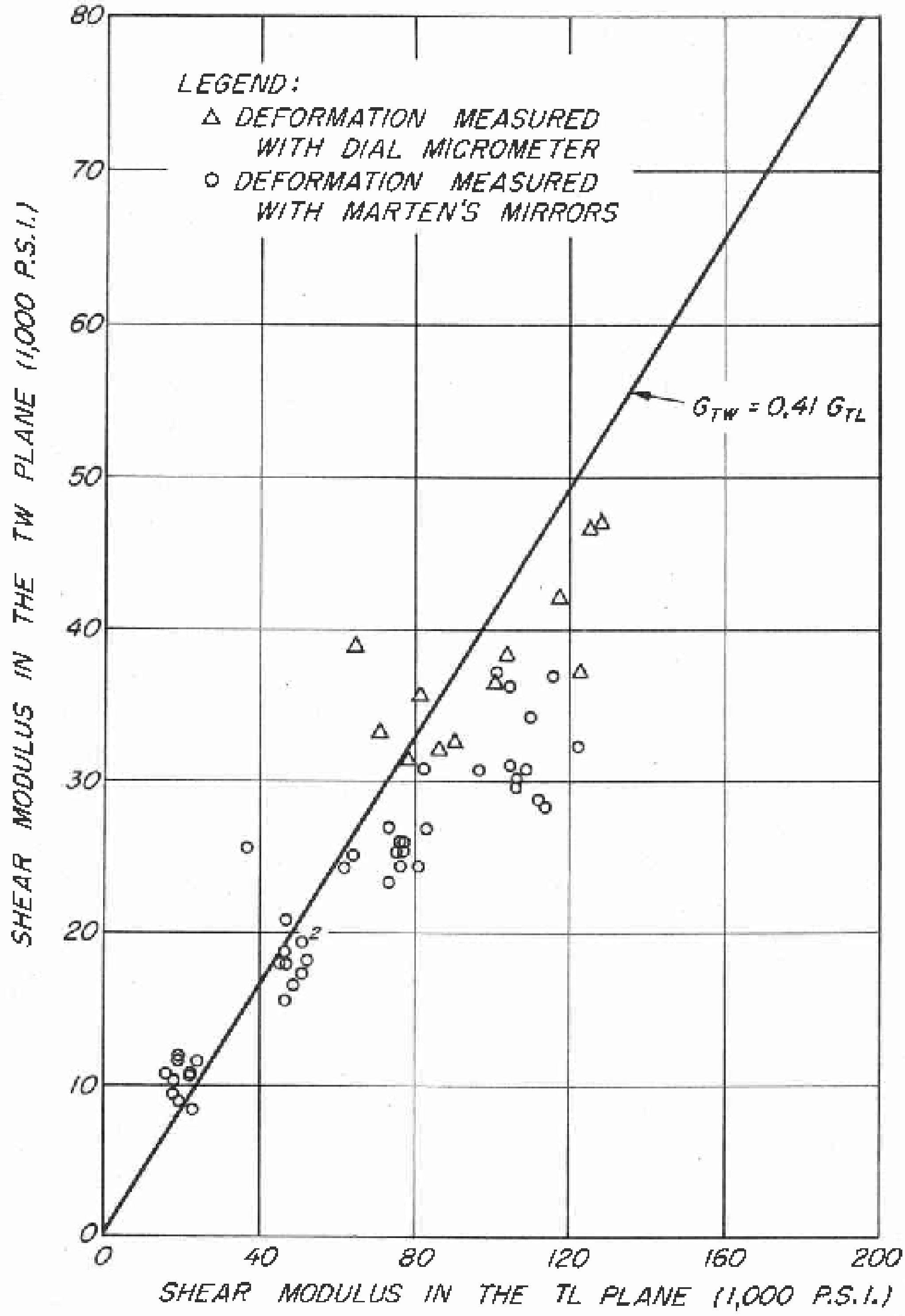

Figure 6. --Comparison of TW shear modulus G_{TW} with TL shear modulus G_{TL} of expanded 5052H39 aluminum honeycomb cores with hexagonal 1/4-inch cells.

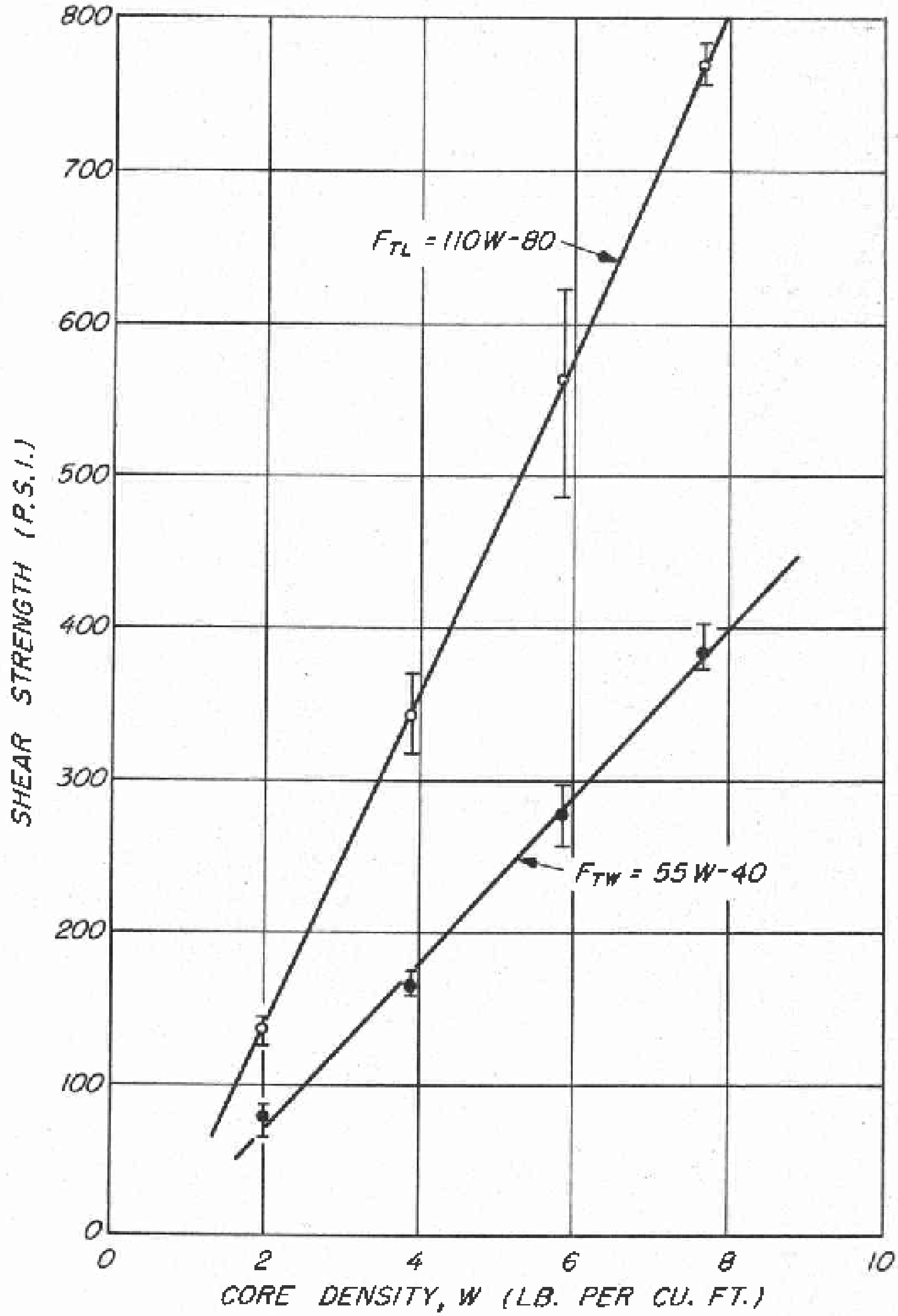

Figure 7.--Minimum, average, and maximum shearing stress values for aluminum cores of 5052H39 alloy with 1/4-inch hexagon-shaped cells.

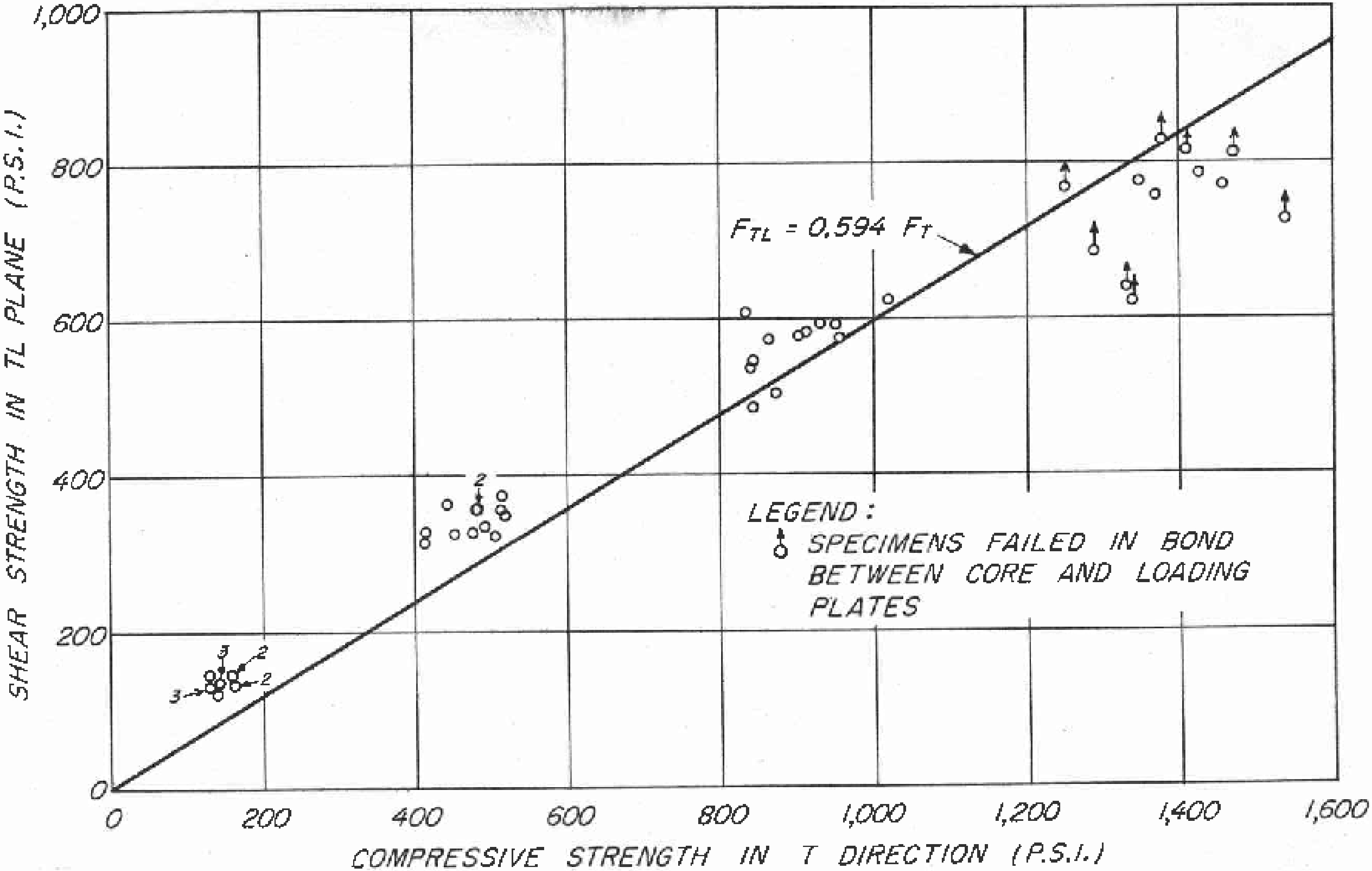

Figure 8.--Relationship between TL shear strength and compressive strength for 5052H39 aluminum honeycomb cores with hexagonal 1/4-inch cells.

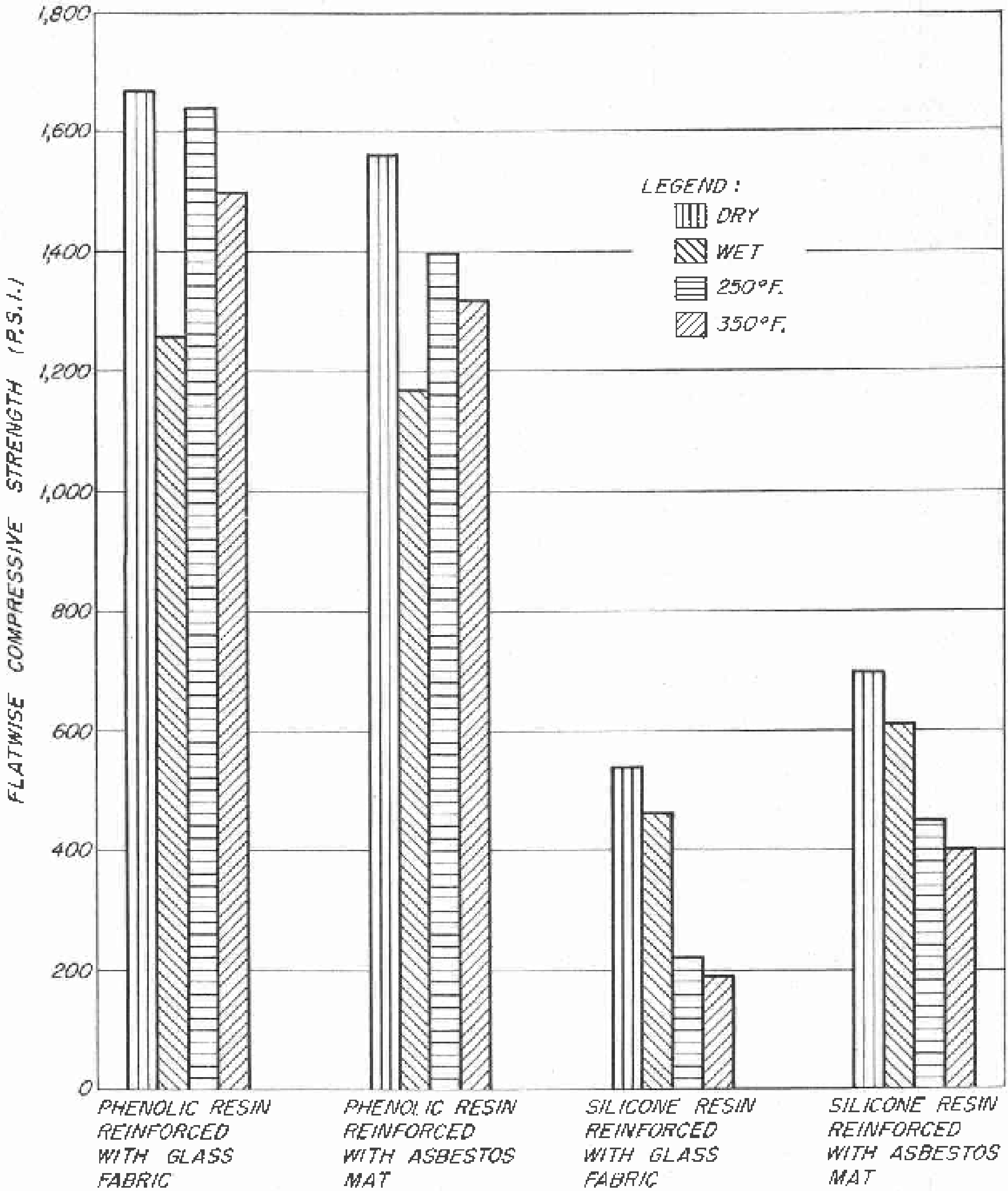

Figure 9. --Average values of compressive strength for reinforced plastic cores of 9 pound-per-cubic-foot density at various test conditions.

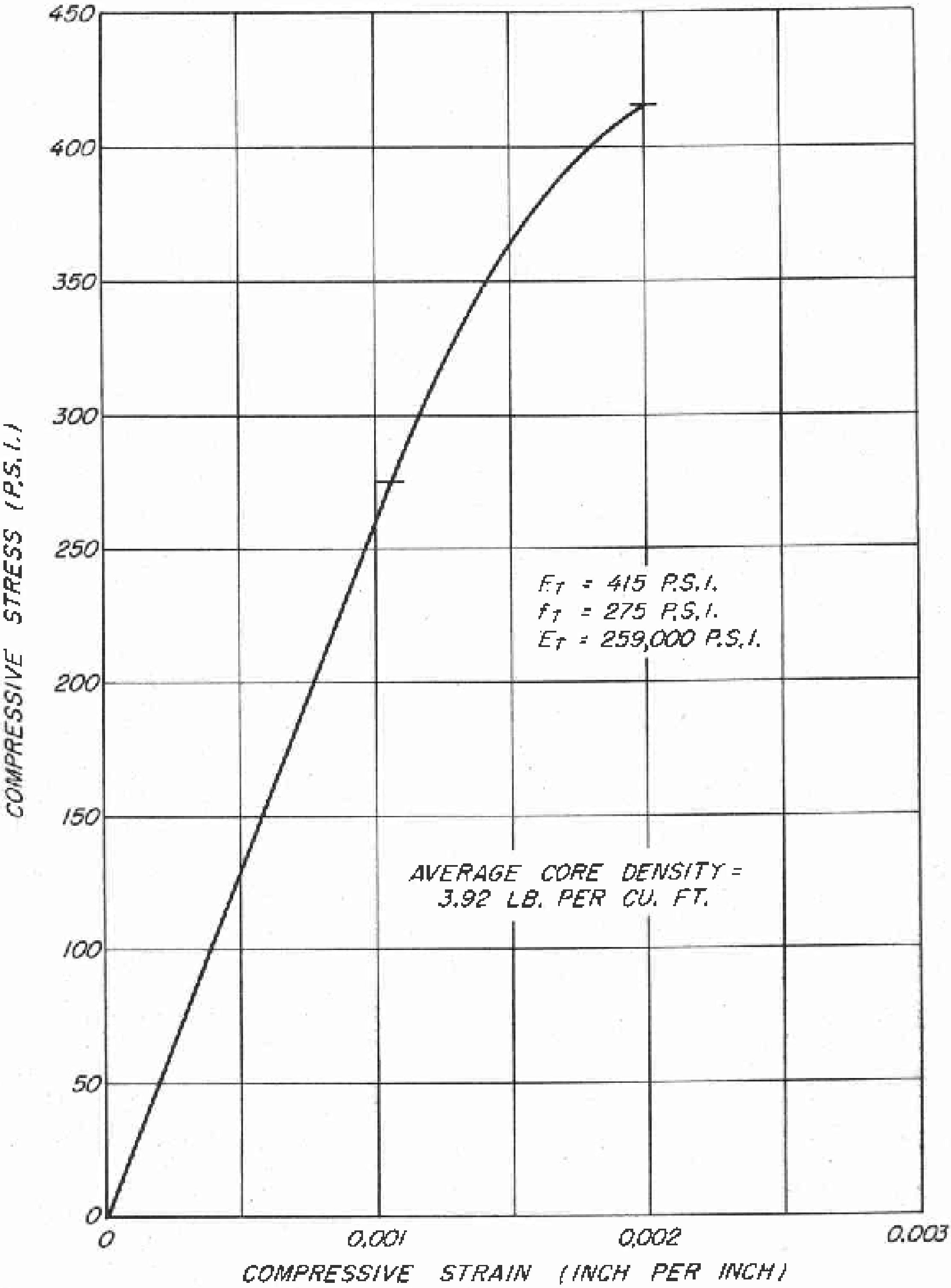

Figure 10. --Compressive stress-strain design curve for aluminum alloy 5052H39 honeycomb core of 0.002-inch perforated foil expanded to 1/4-inch cells.

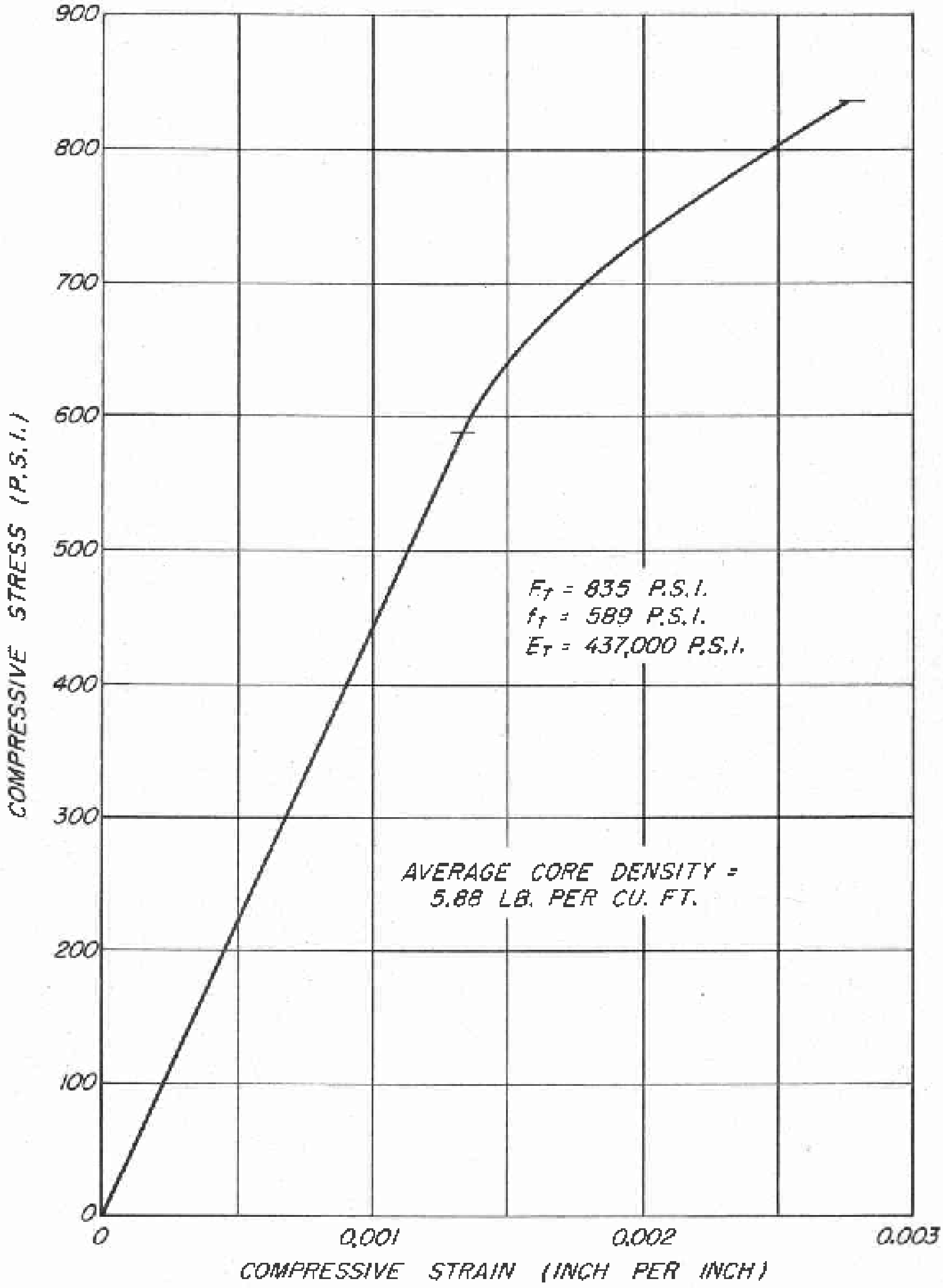

Figure 11.--Compressive stress-strain design curve for aluminum alloy 5052H39 honeycomb core of 0.003-inch perforated foil expanded to 1/4-inch cells.

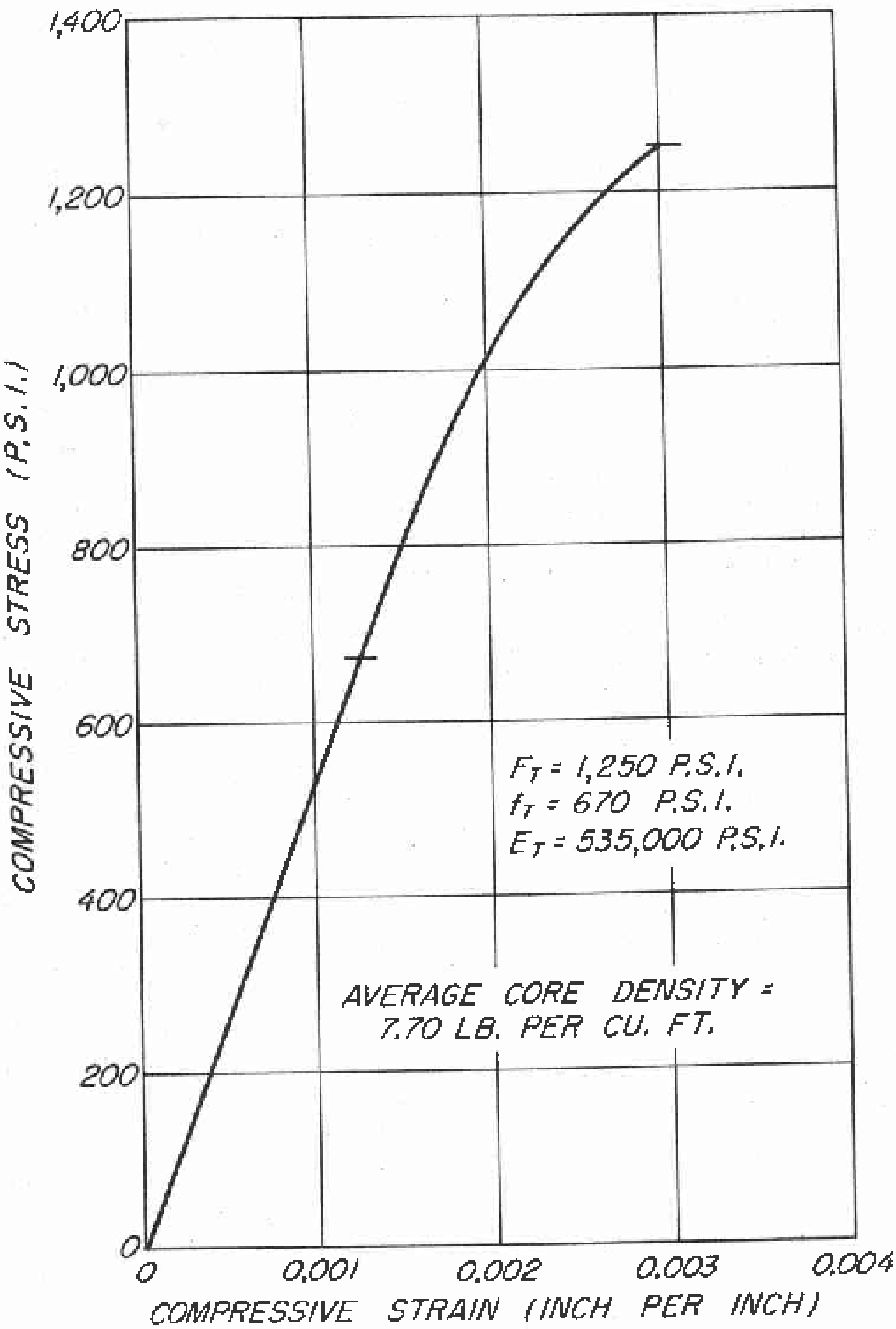

Figure 12. --Compressive stress-strain design curve for aluminum alloy 5052H39 honeycomb core of 0.004-inch-thick perforated foil expanded to 1/4-inch cells.

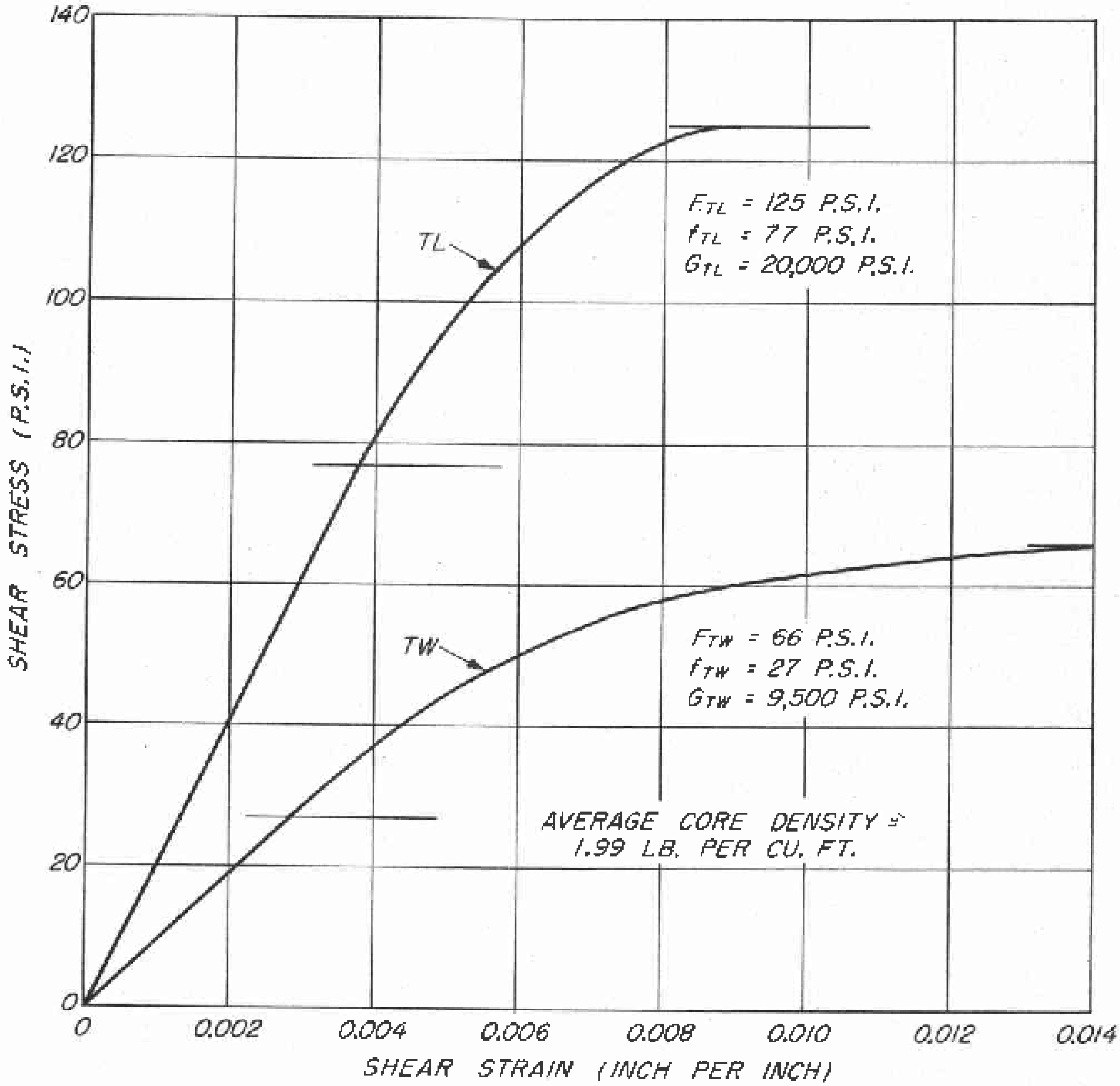

Figure 13. --Shear stress-strain design curves for 5052H39 aluminum honeycomb core of 0.0007-inch foil expanded to 1/4-inch cells.

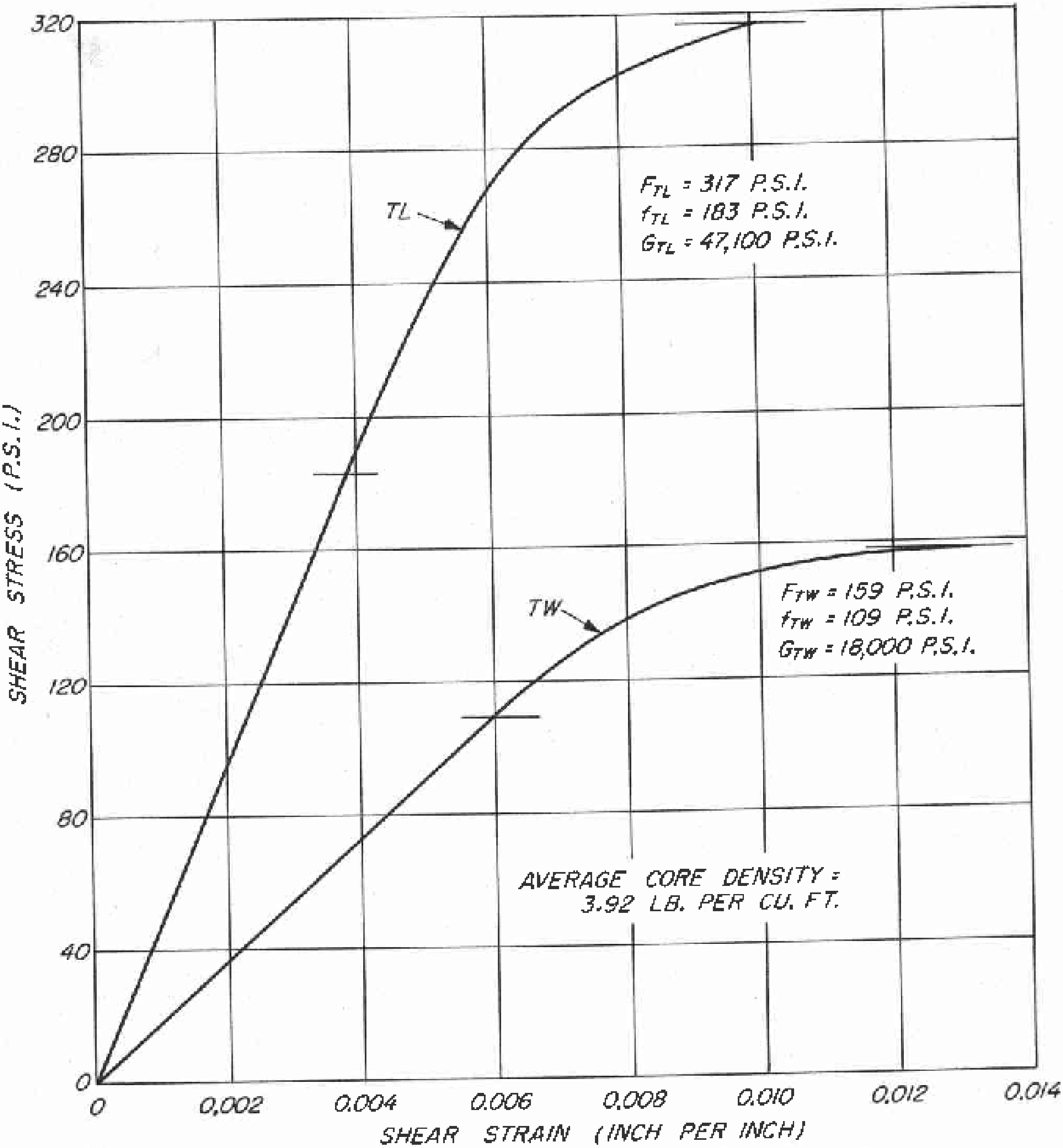

Figure 14.--Shear stress-strain design curves for 5052H39 aluminum honeycomb core of 0.002-inch foil expanded to 1/4-inch cells.

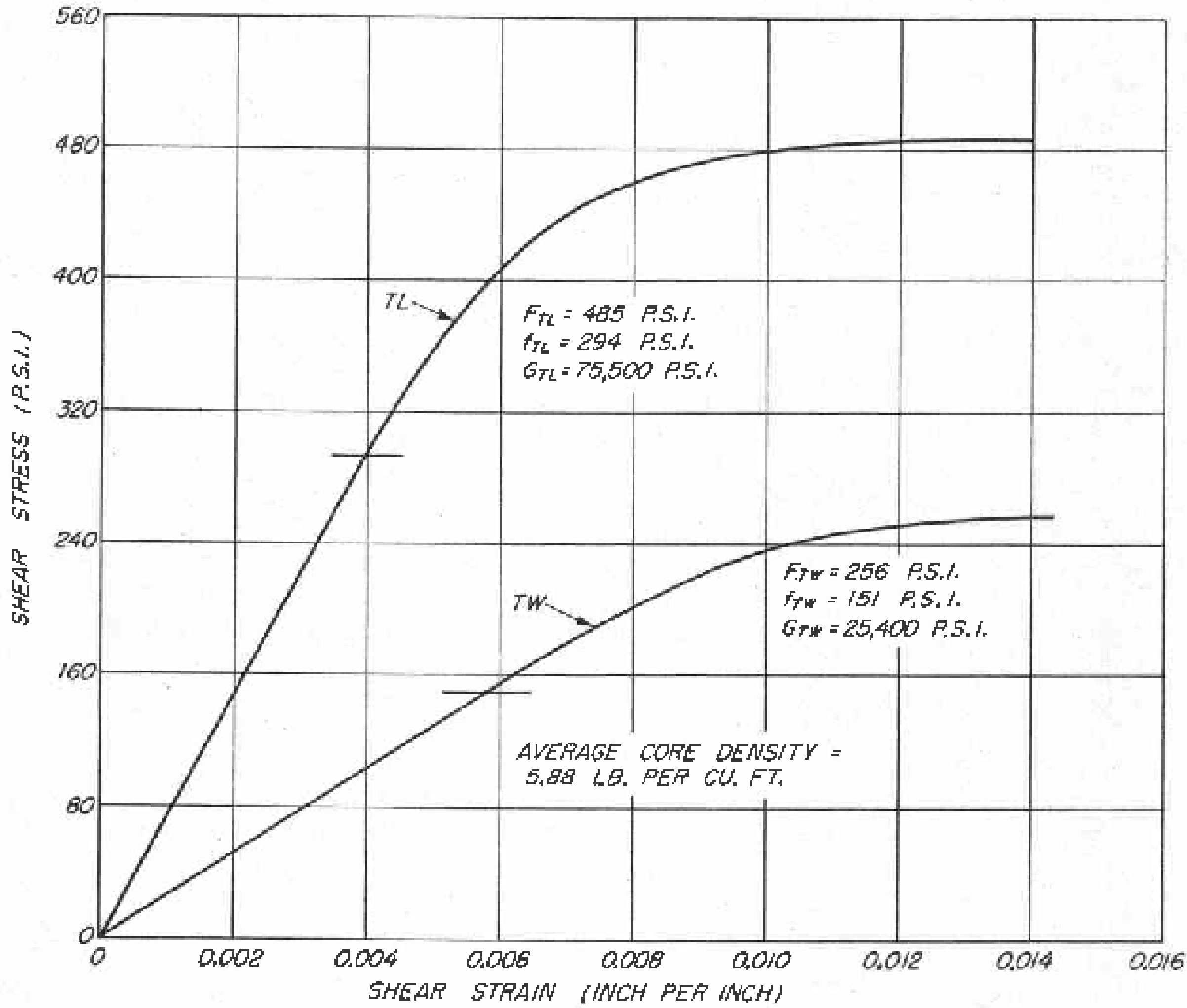

Figure 15. --Shear stress-strain design curves for 5052H39 aluminum honeycomb core of 0.003-inch foil expanded to 1/4-inch cells.

Report No. 1887

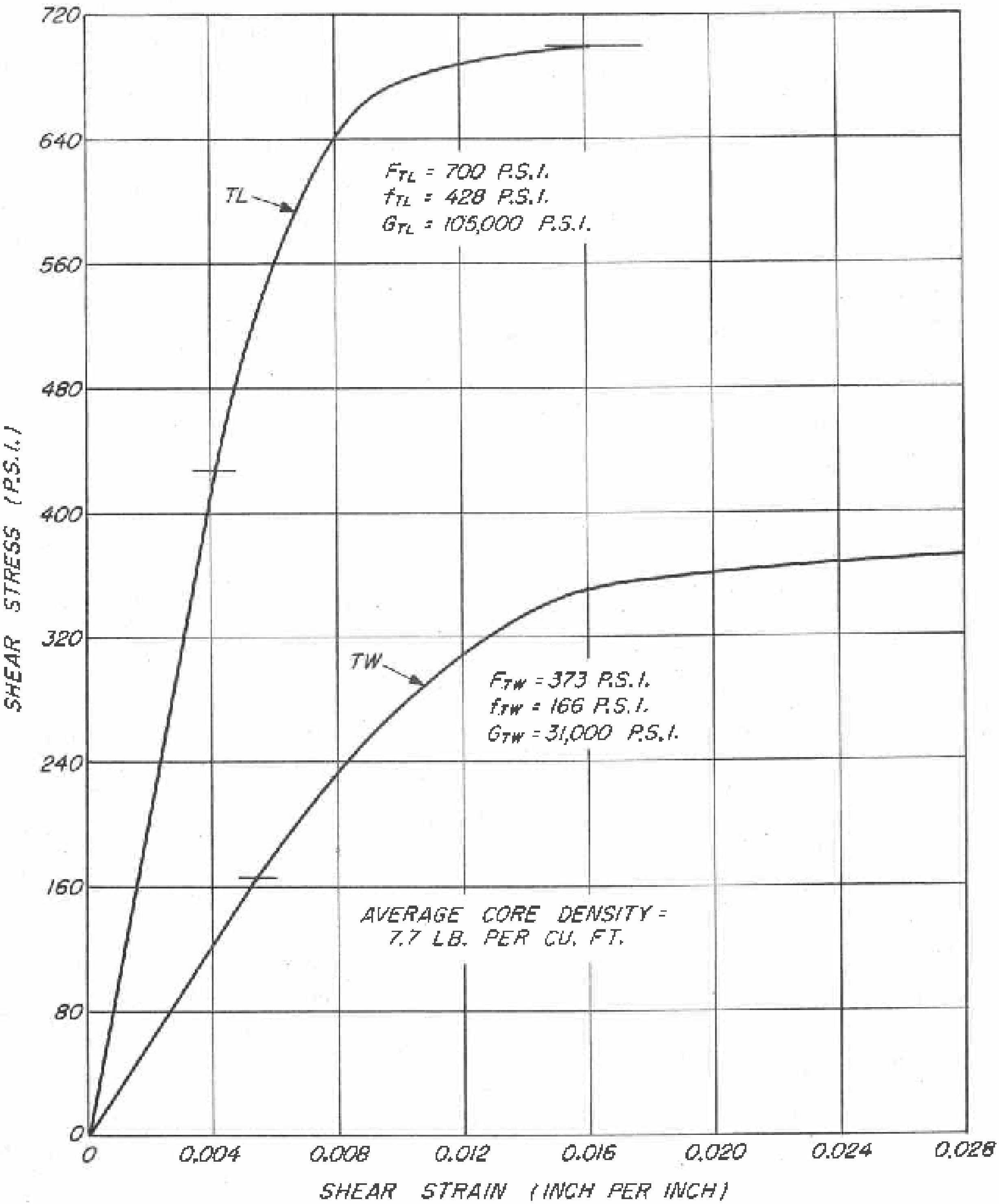

Figure 16.--Shear stress-strain design curves for 5052H39 aluminum honeycomb core of 0.004-inch foil expanded to 1/4-inch cells.